

Numerical Models of Scaffolding Decks and Their Applications

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Abstract This study presents methods for numerical modelling and the static computer analysis of steel decks fixed on scaffoldings. The main problem raised here is the method of creating models of a single deck and determination of the accuracy of every model for various design situations: the analysis of state stress in components of decks, the strength analysis of scaffolding, where decks can be loaded by untypical the arrangement of materials, and the strength analysis of full scaffoldings. The analysis of a state stress in components of a deck requires a detailed model. The analyses of scaffoldings with load by materials have to be performed with using more simple models of platforms. The static-strength analysis of full scaffoldings with many frame elements can be performed if the simplest models of decks are used. In this paper, the sets of truss elements replace the stiffness of scaffolding decks.

Keywords Steel structures · Scaffolding · Numerical models · Static calculations · Finite-element method (FEM)

1 Introduction

Scaffoldings are temporary structures commonly used during building works. Owing to the fact that they are mass-produced elements, all, even slight ones, reductions in the cross sections of elements causes significant savings. Obviously, the producers who seek the reduction of costs take

advantage of this fact. Unfortunately, a side effect of such an activity is the reduced load capacity. The task of the designer, however, is to design a structure with the lowest possible material consumption and which will achieve the assumed load capacity. The use of decks on scaffoldings is essential, because it is on them that workers (the users of scaffoldings) move, and thus, the proper design of platforms ensures the safety of these people. Furthermore, the decks play another role too, i.e., they connect other structural elements of scaffoldings and brace the structure in the horizontal plane. On the other hand, decks have complex shapes, which make it difficult to model this part of a scaffolding in computer analysis, and necessitates the application of equivalent schemes. Several numerical models of decks, together with their use in the assessment of the load capacity of platforms and then in the static analysis of the entire scaffolding, are presented in the study. The numerical results are compared with the results of the laboratory test which were available, courtesy of Altrad Mostostal. The numerical researches concern the engineering application, and therefore, they are mainly conducted for linear material properties. A similar approach to engineering problems is presented in such works as [1, 2].

Before turning to the presentation of the methods for creating numerical models of decks and their use in the static analysis, it ought to be pointed out that the issues of the static work of scaffoldings are rarely featured in the literature. The authors encountered barely a few works addressing strength tests [3–8] or analyses of the reasons for collapses [9–11]. And thus, Halperin and McCann [11] in their work, which tests the load capacity of structures built in the eastern regions of the USA, stated that 32% of scaffoldings are threatened with accidents or disasters. Moreover, it is also stated that there exists no correlation between the poor condition of the scaffolding and the region, the dimensions

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of the scaffolding, or the number of users. It shows how little attention is paid to such kinds of structures at the risk of human lives.

2 Numerical Models of Platforms

2.1 The Structure of Platforms

Scaffoldings decks are elements working in the horizontal plane. Each bearing element rests on horizontal transoms with the use of specially-shaped catches which provide a hinged connection of these elements with the scaffolding. Decks are elements which directly transfer all operation loads to other structural elements in the scaffolding. In addition, decks increase the stiffness of the scaffolding in the horizontal planes. The decks of most of the systems available at the European market are similar to each other, which also allow their use in other systems. In the study below, comes the description of the steel decks produced by Altrad Mostostal, the decks being made of S235JRG2 steel with Young's modulus equal to $E = 2.05 \times 10^8$ kPa, the weight density $\gamma = 78.5$ kN/m³, and the yield strength $f_d = 283$ MPa. Decks are available in two widths—160 and 320 mm—and in the lengths 732, 1088, 1572, 2072, 2572, and 3072 mm. The deck is made of three parts connected with each other by means of welds. The presented modelling methods may be applied to all the dimensions mentioned, while in this work, the calculations will be made for the most unfavourable situations, i.e., for decks measuring 320 mm × 3072 mm, used on 3072 mm × 3072 mm working platforms.

The central largest element of the deck, labelled No. 1 in Fig. 1 is the specially-shaped 1.5-mm-thick metal plate. In the upper part, the metal plate is perforated, which additionally increases its stiffness and at the same time improves the safety and comfort of work. On both sides, the deck is finished with a 1.5-mm-thick metal plate, formed in the shape of a channel. The element is labelled No. 2 in Fig. 1. On both sides, the deck is finished with a pair of catches, marked No. 3 in Fig. 1. The catches are made of a 4-mm-thick metal plate. These elements are the connections of the deck with the horizontal transom. There are two kinds of catches, the first one facilitating the suspension of the deck on the u-profile, whereas the other one, with its shape, being matched to the o-transom.

2.2 A Description of the Numerical Models of the Decks

As it is shown in Fig. 1, the generation of the proper model of the deck, in which all the details of the deck geometry would be taken into account, requires the creation of a model containing very many shell elements and hence very many nodes and degrees of freedom. Such a model would not be useful in practice, because the calculations of even the simplest cases of loads within the linear calculations will be protracted, while the non-linear calculations are impossible to make within a reasonable time. Furthermore, too big a model of one deck does not allow to take into account the co-functioning of several decks, creating a single working platform and moreover, it cannot be used on the whole scaffolding. On account of this, three models are proposed in the work:

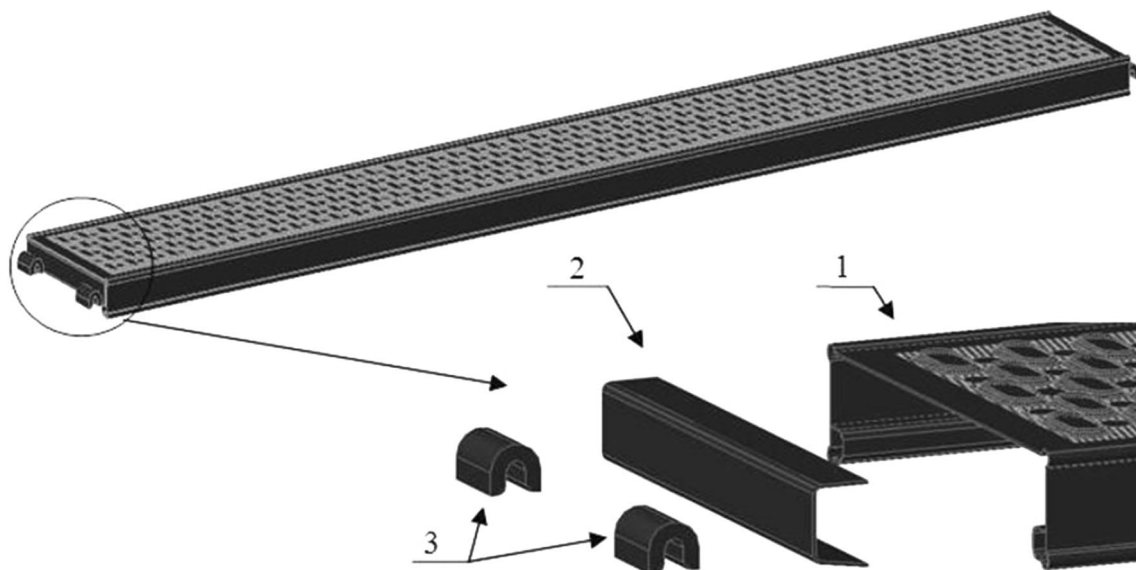


Fig. 1 Steel decks produced by ALTRAD MOSTOSTAL

- model No. 1—a spatial exact model of one deck, in which the perforated metal plate is replaced with a shell-beam model, it can be used both linear and non-linear static analyses into condition that the stresses in modified plate elements do not achieve yield strength,
- model No. 2—a simplified plate model, in which shell and beam elements are applied,
- model No. 3—a system of truss elements, used only for forming the stiffness of the decks and non-transferring loads; the imposed loads may be transferred only by the shell elements of such dimensions as in the case of one FEM element corresponding to one deck.

The models No. 2 and No. 3 can be used only in linear static calculations. All calculations are performed with the use of the Autodesk Simulation Mechanical system.

2.3 The Construction of Model No. 1

The first stage in the construction of the detailed model is the creation of a model for a section of the perforated metal plate. To define the characteristic properties of the substitute material for the metal plate, a comparison of the displacements taken from the model of an exact section of the metal (Fig. 2a) with the displacements of the substitute model (Fig. 2b) is performed, aiming to minimise the difference in deflections between those two models. To determine the substitute model of the plate, a square model of the section of the perforated metal plate 250 mm × 250 mm is used, as indicated in Fig. 2. In the FEM model, a mesh is made from elements with the size of edges equal to about 1.0 mm, which allows the exact representation of all the curvatures of the perforation, which at the same time complies with the limitations imposed by the used calculation program.

Subsequently, the model with the rigid fixing on one side is loaded with forces applied to one edge of the model, with a resultant value equal to 1.0 kN. The two instances of load, presenting the work of the metal plate

in two directions, are here adopted. In the first case, the load is applied to the edge of the bracket, parallel to the length of the deck (along the y -axis in Fig. 2). In the second case, the load is applied to the edge of the bracket, perpendicular to the length of the deck (along the x -axis in Fig. 2). In the substitute model, in the first step, the same thickness for the plate elements and characteristic material properties as in the detailed model are adopted. Then, the analysis is performed for each case of analogous loads, as in the detailed model. The next step is the enhancement of the properties of the materials used in the substitute section. For this purpose, a comparison of the displacement obtained from the detailed and the simplified models which are loaded in the same way is performed. In the following calculation steps, the values of the properties of the substitute material are corrected to minimise the difference in the displacements. It allows obtaining the properties of the material in the substitute model, sought for the first instance of load. What comes out from the analysis of the results and the visual assessment of the perforation shapes is that the deck plate could be treated as an isotropic one.

Thus, to obtain the better agreement of the displacements of the both analysed models for both cases of loads, the beam elements are added which, in consequence, increases the stiffness of the model in the direction perpendicular to the length of the deck. The properties of the material of the beam elements are also determined by the application of the iterative method. Finally, in the substitute FEM model, beams are used with geometric and material properties described in Table 1, and shell elements with weight density equal to $\gamma = 78.5 \text{ kN/m}^3$, Young's modulus $E = 3.2 \times 10^8 \text{ kPa}$, Poisson's ratio $\nu = 0.3$ and the thickness of 1.5 mm.

The other fragments of the single deck model are modelled with shell elements, the welded joints of the handles and deck—with three-dimensional elements (called “bricks” in the element library of the Autodesk Simulation Mechanical system).

Fig. 2 Numerical model of a segment of perforated metal plate

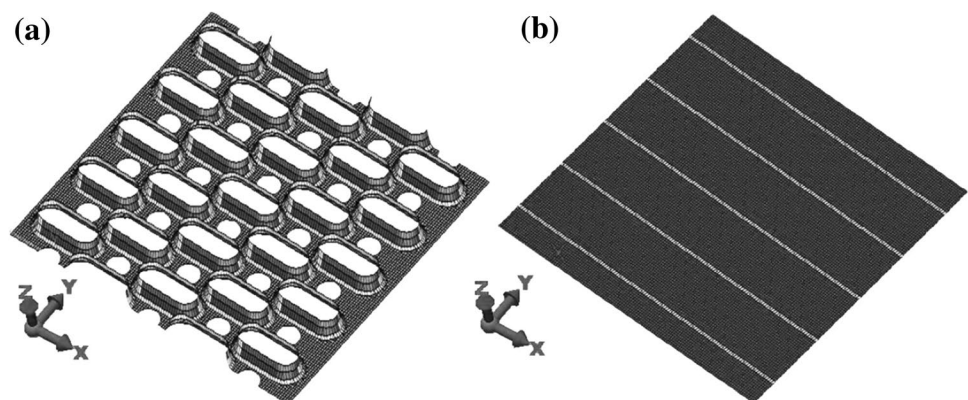


Table 1 Geometrical and material characteristics of beam elements

| Cross-sectional characteristics | | Material properties | |
|---------------------------------|------|-------------------------------------|-----------------------|
| A [mm ²] | 0.1 | Weight density [N/mm ³] | 7.85×10^{-5} |
| I_s [mm ⁴] | 0.1 | Young's modulus [kPa] | 3.2×10^5 |
| I_x [mm ⁴] | 0.1 | Poisson ratio | 0.3 |
| I_y [mm ⁴] | 27.0 | | |

A area of the cross section, I_s torsion constant, I_x and I_y moments of inertia with regard to the x - and y -axes, respectively

2.4 The Construction of Model No. 2

Unfortunately, the model described above contains a large number of degrees of freedom which means that it cannot be used in the model of complete working platforms, composed of several decks. With relation to this, model No. 2 is prepared, in which the catches, the front metal plate, and the sides of the deck plate are modelled as beam elements, the central metal plate being modelled with shell and beam elements, like in model No. 1 (see Fig. 3).

The material properties are accepted as for steel, i.e., weight density equals $\gamma = 78.5 \text{ kN/m}^3$, Young modulus $E = 2.0 \times 10^8 \text{ kPa}$, and Poisson ratio $\nu = 0.3$. The first step is to define the initial geometrical characteristics of the beam elements, which consists in adopting the geometrical characteristics of the cross sections of particular parts of the deck. The results of the calculations are shown in Table 2. Then, for the purpose of defining the final geometrical characteristics of the elements in model No. 2, the displacements obtained from models No. 1 and No. 2 which are loaded in the same way are compared.

This iterative method consists in the correction of values of moments of inertia of beam elements, aimed at minimising the difference between the deflections of these two models. To create as universal a model as possible, three cases of loads are here analysed:

- Case No. 1—the load is applied uniformly to the deck of the whole area of 2.0 kN/m^2 .
- Case No. 2—the load is applied to the deck in the middle of its span at 1 m length; with the value of 6.0 kN/m^2 , it is at the resultant force equal to 1.92 kN .
- Case No. 3—the load is applied to the deck at one side at 1 m width, with the value of 6.0 kN/m^2 .

The first stage consists of the load application to the detailed model (model No. 1) and simplified model (model No. 2) according to the three instances of loads described above. Subsequently, the displacements, obtained at the height of the centre of gravity at the side of the deck in the detailed model, are compared to the corresponding displacements on the side of the simplified model. The next step concerns the determination of the final properties of the material in the elements of the simplified model. It consists in the correction of the moment of inertia of the cross section for beam elements, aiming at minimising the differences between deflections. The ultimately accepted geometrical characteristic of the beam elements is shown in Table 2. The calculation results were confirmed by measurements. The Altrad Mostostal concern gave the information that the vertical displacement of the deck scaffolding was equal to 8.7 mm at the force equal to 1.3 kN which is located in the middle of deck. The vertical displacement obtained from calculation for case No. 2 is equal to 12.77 mm at the force equal to 1.92 kN . It means that the difference between calculations and measurements is equal to about 0.5% .

2.5 The Construction of Model No. 3

As mentioned earlier, it is impossible to use the detailed models of the scaffolding decks in the whole structure. Even model No. 2, due to the number of elements of which it is made, allows simultaneous calculations for only a dozen decks or so decks. Thus, in the static calculations

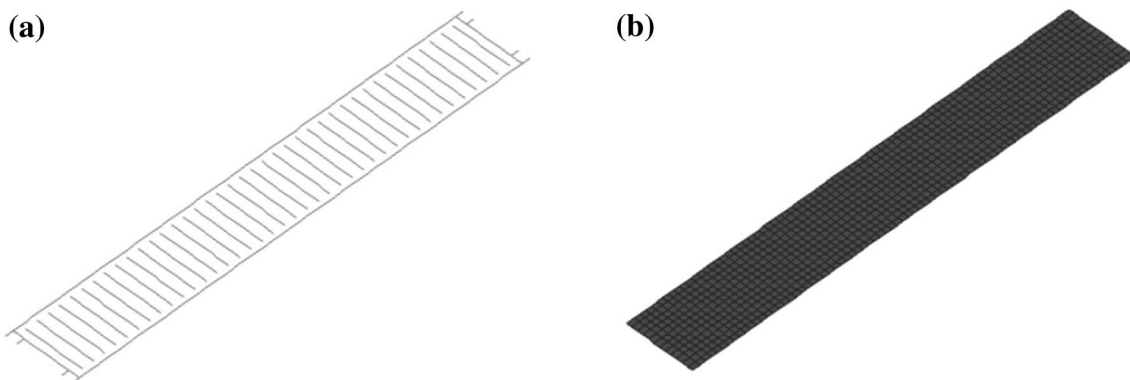
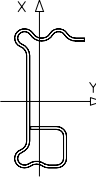
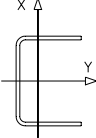
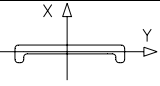
**Fig. 3** Fragment of deck model No. 1

Table 2 Geometrical characteristics of beam elements in model No. 2 for a deck of dimensions: 3072 mm × 320 mm

| Side of central plate (element No. 1 in Fig. 1) | First approximation characteristics | | Final characteristics | |
|---|--|----------|--------------------------|----------|
|  | A [mm ²] | 259.0 | A [mm ²] | 259.4 |
| | I_s [mm ⁴] | 191.0 | I_s [mm ⁴] | 191.2 |
| | I_x [mm ⁴] | 20095.0 | I_x [mm ⁴] | 20095.3 |
| | I_y [mm ⁴] | 185470.0 | I_y [mm ⁴] | 316100.0 |
| Both plate (element No. 2 in Fig. 1) | | | | |
|  | A [mm ²] | 174.0 | A [mm ²] | 174.0 |
| | I_s [mm ⁴] | 241.0 | I_s [mm ⁴] | 241.0 |
| | I_x [mm ⁴] | 25007.0 | I_x [mm ⁴] | 25007.0 |
| | I_y [mm ⁴] | 61127.0 | I_y [mm ⁴] | 61127.0 |
| Catches (element No. 3 in Fig. 1) | | | | |
|  | A [mm ²] | 232.0 | A [mm ²] | 232.0 |
| | I_s [mm ⁴] | 170.0 | I_s [mm ⁴] | 170.0 |
| | I_x [mm ⁴] | 222.0 | I_x [mm ⁴] | 222.0 |
| | I_y [mm ⁴] | 170.0 | I_y [mm ⁴] | 150.0 |

of scaffoldings, the model which represents the horizontal stiffness of the deck and its weight should be used, while the stresses in the structure of the deck in the case of atypical loads should be considered separately for particular moduli of the scaffolding. The model of deck No. 3, which could be used in the static calculations of the scaffoldings, is made of four truss elements. To determine mechanical characteristics of these elements, the scaffolding section was loaded with the force in the decks' horizontal plane. For this purpose, below are described the measurements results which were made available by the Altrad Mostostal concern. The described test was conducted on the base of the standard EN 12810-2 [12]. The force was introduced with the use of the hydraulic cylinder. The force measurement was made with the force transducer attached to the end of the hydraulic cylinder. The displacements of

the outer stands were measured with three sensors. The mounted scaffolding section was settled with roller supports. There were outer stands adjacent to the wall attached to the retaining wall of the test site with use of the anchor connectors mounted in the "V" shape. The test site is presented in Fig. 4a, while the static scheme of the test in Fig. 4b. The result of the test is the determination of the system stiffness. Its average value from six tests is equal to 0.402 kN/mm for linear part of the σ – ϵ graph.

Two models of the scaffolding were created on the basis of the test. The elaborated models were loaded with the concentrated force of magnitude 8.0 kN applied to the outer node of the deck in the horizontal plane. In the first model of the scaffolding section, the deck plates were replaced with the model No. 2 of the decks. The displacement values obtained with use of this model from numerical

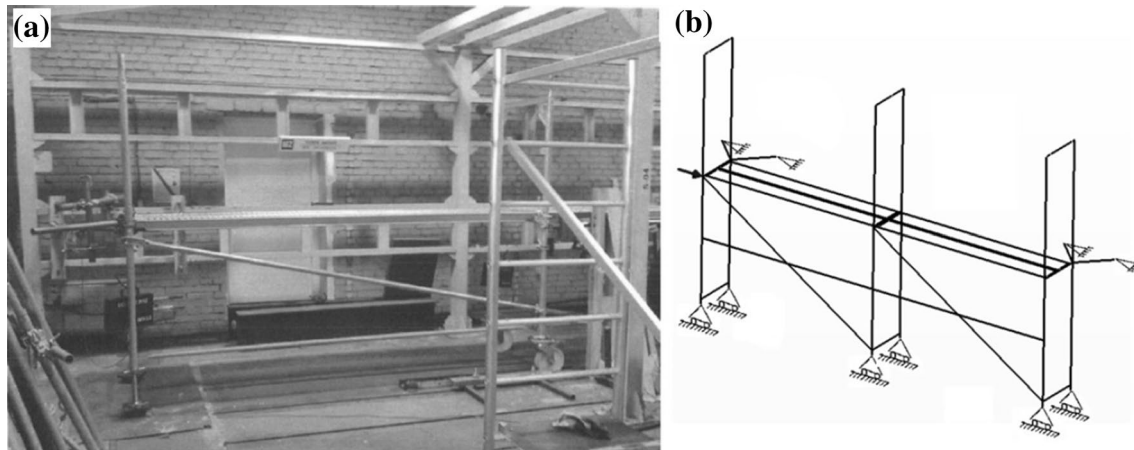


Fig. 4 Test arrangement: **a** position of in the laboratory (courtesy of the Altrad Mostostal concern), **b** test static scheme

analysis are presented in Fig. 5a. As it can be seen, there was good agreement, because the calculated stiffness is equal to 0.396 kN/mm. In the next model of the scaffolding section, each deck was replaced with four truss rods: two parallel ones to each other and two crossing ones. The cross-sectional areas of the crossing truss elements are chosen to replace the scaffolding decks stiffness in direction perpendicular to the plane of scaffolding. The cross-sectional areas of two other truss elements are chosen to replace the scaffolding decks stiffness in direction parallel to the plane of scaffolding. The values of cross sections are listed in Table 3. This allows easy matching of the stiffness to the values obtained with tests, as well as with numerical analysis when model No. 2 of the deck is used (Fig. 5b). The comparison of the displacements in the two numerical models loaded in the same way also lead to the good agreement conclusion (Fig. 6).

After the comparison of the obtained results, it can be stated that the assumed model accurately reflects the horizontal stiffness of the scaffolding and can be used in the static calculations of the scaffoldings.

3 The Analysis of the Load Capacity of the Platforms

The models of individual decks No. 1 and No. 2 can be used for analysing the effort of decks, depending on the location of the load caused by stored materials with a total weight of 10.0 kN and arranged on the area of 1000 mm × 1200 mm. Owing to the simplification applied to model No. 2, an entire working platform comprised of nine decks is possible to model. In the search for the most unfavourable location of the load in question, linear analyses are performed on many variants, which allow the consideration of all possible locations of the building materials pallet.

To determine the maximum values and the stress distribution in the deck, in model No. 2, the displacements from the deck with the highest effort are read and transferred to model No. 1 through excitations applied at the centre of gravity of the sides of element No. 3. Only a precise model with the load applied in this way could be subjected to a final static analysis allowing the formulation of conclusions concerning the stresses inside the decks. The largest displacements are observed in variant shown in Fig. 7, and for this variant, the highest stresses are noted as well. As shown in Fig. 8a, the biggest values of stresses occur at the grips and in the places where the front and side metal plates connect. These stress values are exaggerated due to the local numerical singularities and on account of the use of static linear analyses.

In the linear analyses, it is observed that decks work virtually independently of each other. The rotations of the sides of the deck are sufficiently low and the decks do not touch each other. This fact is used to determine the stress values inside the deck from the calculations in which the non-linearity of the material is used. The yield criterion is defined on the basis of the Huber–Mises–Hencky hypothesis. Young's elasticity modulus E is adopted as equal to 200 GPa, and the strain hardening modulus is assumed to be a hundredfold smaller. The applied Poisson's ratio equals $\nu=0.3$ and the yield strength is set equal to $f_d = 325$ MPa. Model No. 1 is also modified through mesh optimisation, which has no significant effect on the results. This fact is confirmed by the comparison of stress values obtained from linear analyses of models with various mesh densities.

As expected, in the non-linear analysis, the highest stress values are observed in the same locations as in linear analysis, and with relation to the non-linear model of the material, they result in lower values (Fig. 9). This is reflected in reality, since during the inspection of damaged elements (Fig. 10) which were withdrawn from use, considerable

Fig. 5 Displacements of the scaffolding caused by the force acting along the scaffolding with the use of model: **a** No. 2; **b** No 3

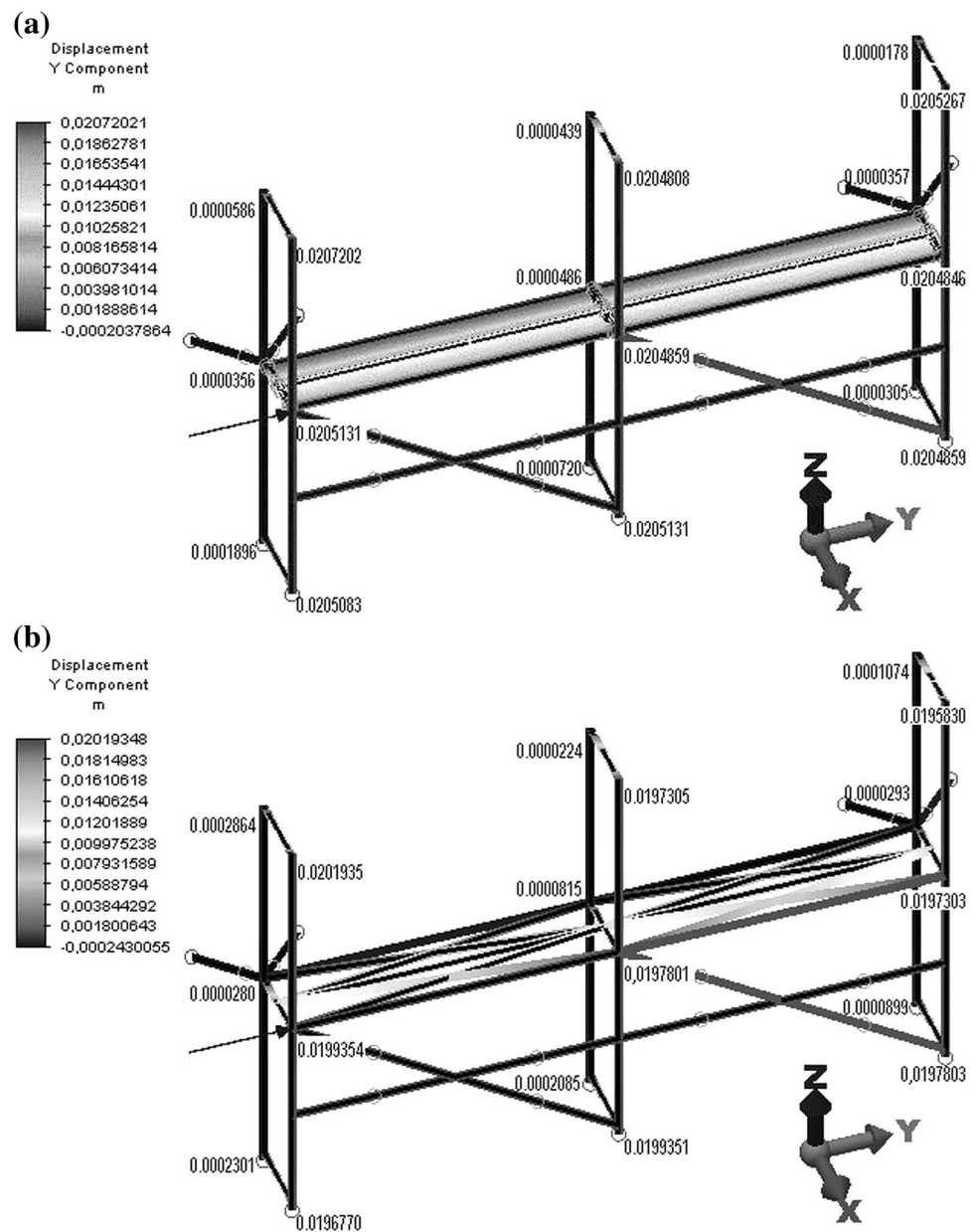


Table 3 Geometrical and material characteristics of truss elements which create model No. 3

| Cross-sectional area A [m ²] | | Material properties | |
|--|-----------------------|-------------------------------------|-------------------|
| Crossing truss elements | 5.65×10^{-4} | Weight density [kN/m ³] | 7.85 |
| Parallel truss elements | 3.10×10^{-6} | Young's modulus [kPa] | 2.0×10^8 |
| | | Poisson ratio | 0.3 |

strains, deformations, and even cracks in material are found in the same locations where stresses concentrate in the computer model.

While analysing the results, the stresses in the centre of the span of the deck are also taken into account. However, the pattern of stresses in this area is of a very mild nature, and the maximum values are far smaller than in the above-mentioned locations. It is of great importance as in the central part, the model correctly reflecting displacements only is used, and the yield criterion is tested only for stresses. Because the stresses of the central part of the metal plate are low, it works within a linear scope and there are no errors caused by the simplification introduced to numerical model No. 1.

Even though it is proven that non-linear analyses are closer to reality, it seems that if there are a large number of cases to analyse or there appears a necessity to use

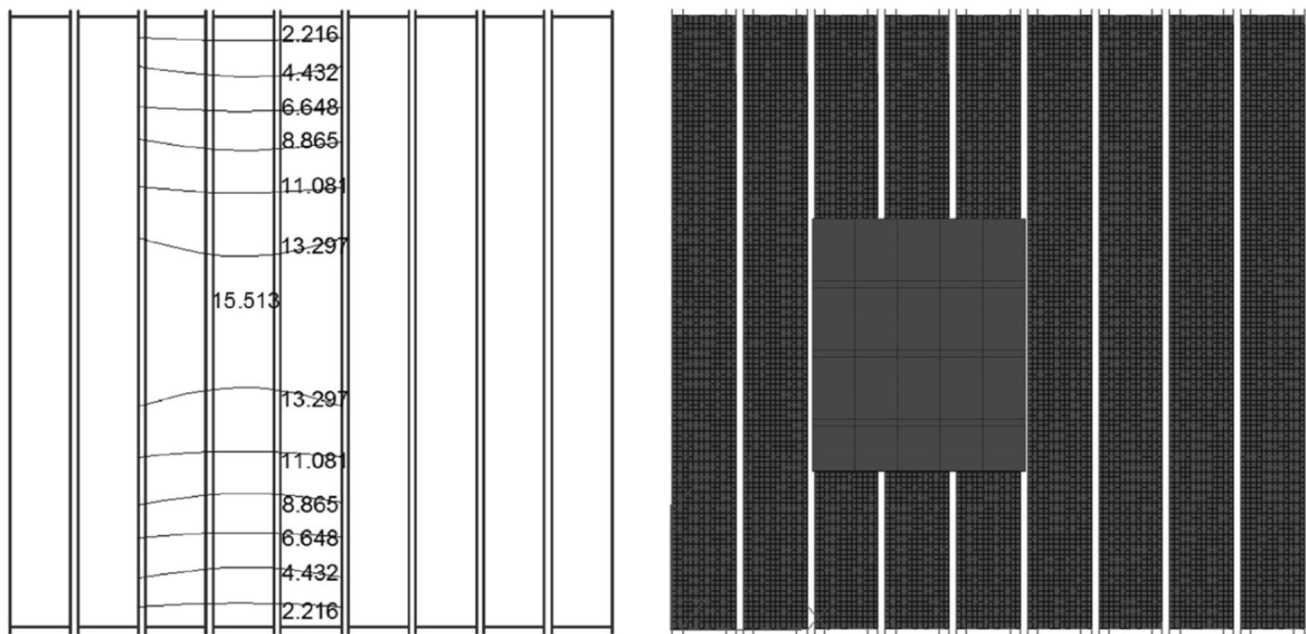


Fig. 7 Load scheme and values of displacements [mm] for the variant with maximum values

location of the materials stored on the platform, a static scheme is created in which most of the decks are replaced with truss elements of model No. 3. An exception is the platform on which the storage of materials is planned. That platform was introduced into the scheme as a set of several decks with the use of model No. 2.

For the static scheme like this the linear analysis for two problems is performed: with the load uniformly distributed and with the load placed as in variant 7, described in point 3. In both problems, the resultant force amounted to 27.0 kN.

The comparison of the results shows that a change in the load system affects only the transoms on which the decks are installed, as well as the vertical standards supporting these transoms. However, the differences in tensions amount to over 50%, which in many cases may mean a loss of load capacity of the structure, and eventually its failure.

In the case of the analysis of the whole structure of the scaffolding without taking such aspects as the location of the load on individual decks into account, it is sufficient to replace individual decks with the set of truss elements (model No. 3), and to apply the load to the shell elements with the dimensions of an individual deck, but with very low stiffness. Thanks to such an approach the obtained scheme describes correctly the real structure without the use of a model with many degrees of freedom, which will either mean that the problem will take a very long time to compute, or for which the analysis of such a model will be impossible to perform.

5 Conclusions

The presented examples of numerical analyses of decks with the use of FEM show that the finite-element method is a very useful tool for defining the load capacity of elements such as steel decks placed on scaffoldings. Nevertheless, due to the complicated shape of the decks, there is a necessity for the application of simplifications: from the creation of models resembling the deck in shape, or models with simplified shapes, to the use of simplification reduced to the set of truss elements which substitute the horizontal stiffness of platforms only both perpendicular and parallel direction with respect to the scaffolding plane. During the analysis of the correctness of the construction of a deck, both model No. 1 and No. 2 ought to be used, though unfortunately in the calculations for the whole scaffolding, considerable simplifications have to be applied, i.e., model No. 3. Furthermore, in performing the numerical tests of the load capacity of the decks, both the calculations with the linear and non-linear models of the material are worth using. The simplifications described in point 2, applied in the model, reduce the scope of its application. Therefore, it is sometimes to use the linear calculations, yet with the awareness that the analysis of load capacity based on the linear analysis only, with the incorrect interpretation of the results of the calculations may lead to the understatement of the load capacity of the decks.

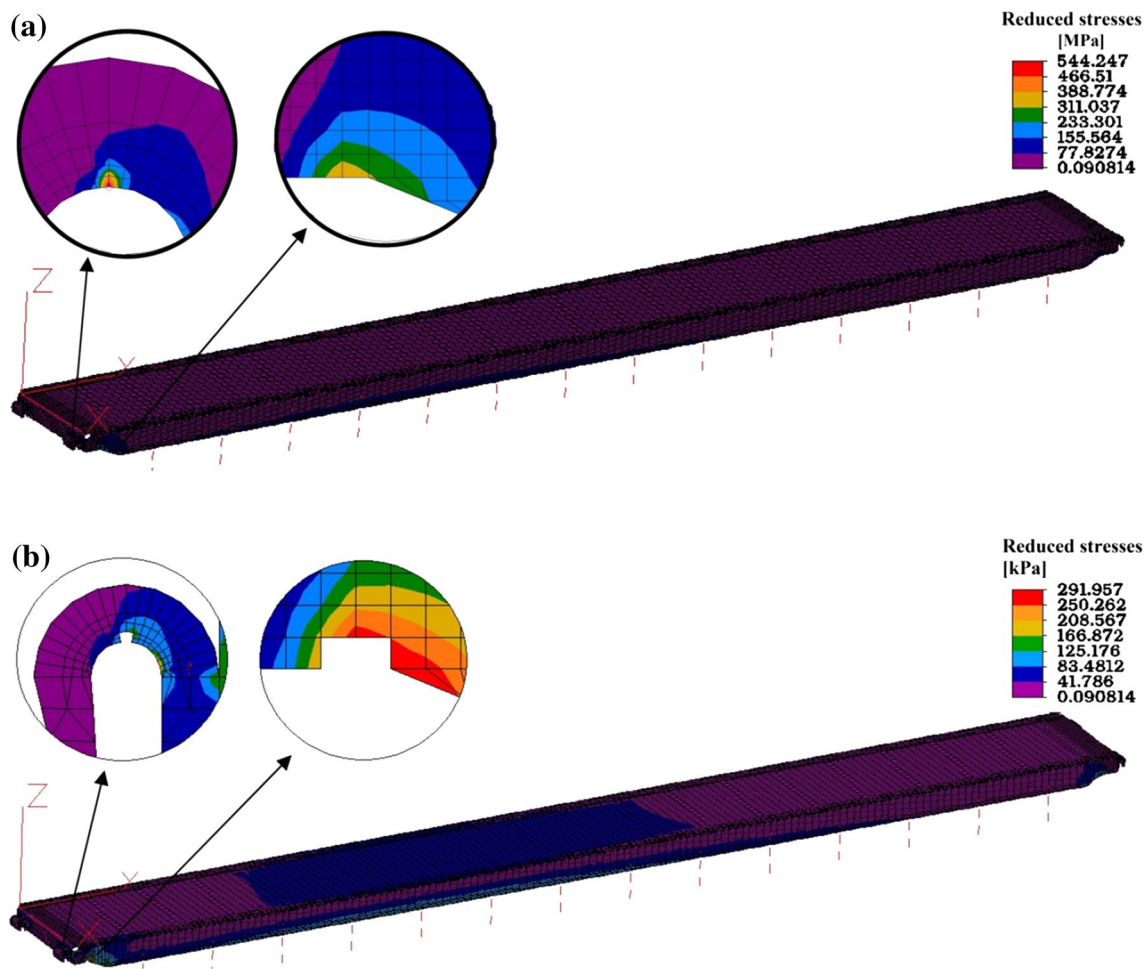


Fig. 8 Huber–Mises–Hencky reduced stresses [MPa] in the most strained single deck, obtained in the linear analysis, **a** without any interference in the results, **b** with omission of stresses at singularity places

Fig. 9 Huber–Mises–Hencky reduced stresses [MPa] in the single deck obtained in the analysis with material non-linearity

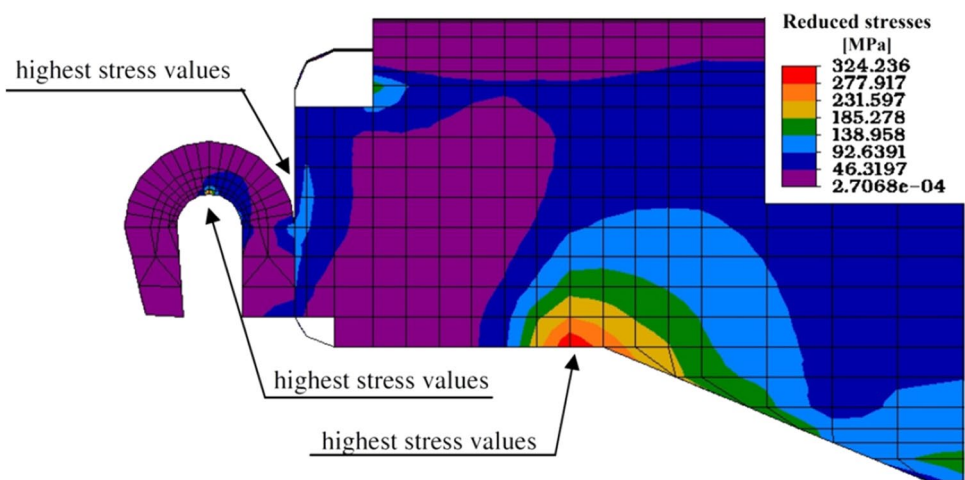
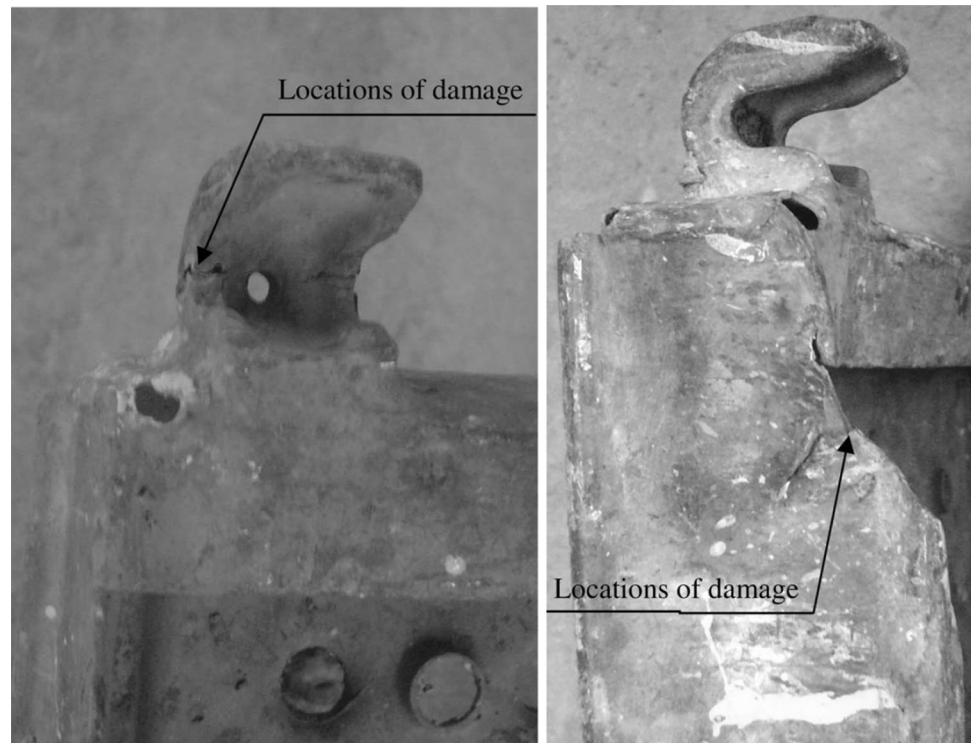


Fig. 10 Locations of damages in decks (own photographs)



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